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Dynamic shear localization in Ti6Al4V

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Abstract

The alloy Ti6Al4V is known to be prone to the formation of adiabatic shear bands when dynamically loaded in shear. This causes a catastrophic decrease of the load carrying capacity and is usually followed by fracture. Although, the main mechanism is recognized to be the competition between strain hardening and thermal softening, a detailed understanding of the role of microstructural plasticity mechanisms and macroscopic loading conditions does not exist yet. To study strain localization and shear fracture, different high strain rate shear tests have been carried out: compression of hat-shaped specimens, torsion of thin walled tubular specimens and in-plane shear tests. The value of the three techniques in studying shear localization is evaluated. Post-mortem analysis of the fracture surface and the materials' microstructure is performed with optical and electron microscopy. In all cases a ductile fracture is observed. SEM and TEM techniques are used to study the local microstructure and composition in the shear band and as such the driving mechanism for the ASB formation.

Keywords: Ti6Al4V, high strain rate, Hopkinson, shear band, microscopy

1. Introduction

Adiabatic Shear Bands (ASBs) are a thermodynamic phenomenon characterized by high strain rates and large deformations localized in a narrow band of 5μm to 100μm [1]. They are observed in many applications such as machine chips, forging, ballistic impact loading... In most cases the occurrence of adiabatic shearing is undesirable. On the other hand, recently developed adiabatic cutting and blanking techniques make explicitly use of the ASB phenomenon. The formation of ASBs causes the material to

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lose its load carrying and energy dissipative capacity. Moreover, adiabatic shearing is known to be a precursor to failure. Therefore it is important to understand the whole process from localization to failure.

The mechanism proposed by Zener and Hollomon [1], based on the destabilizing effect of thermal softening due to plastic work converted into heat, is generally accepted as the explanation for the formation of adiabatic shear bands. On the other hand, the role of microstructural plasticity mechanisms and macroscopic loading conditions such as the size, shape and orientation of grains, inclusions and stress triaxiality is much less clear. An experimental study, involving different loading conditions together with in depth microstructural investigation is needed.

Ti6Al4V is known to be sensitive to adiabatic shearing and subsequent failure [1]. This is mainly due to its low density and heat conduction. Because of the great practical importance of Ti6Al4V a lot of research has already been conducted on the subject of adiabatic shear banding. Thereby, several high strain rate experimental techniques have been used: torsion of thin walled tubes, thick walled cylinder implosion test, modified double shear test, shear-compression specimen tests [2]… Usually, in each study one single experimental technique is used with its own advantages and disadvantages.

In this study, three different high strain rate experimental techniques are used to dynamically deform Ti6Al4V in shear. In this way, complementary information about the materials' dynamic shear behaviour, including adiabatic shear bands, is acquired. In this study, the value of the three techniques to study shear localization is evaluated. One technique is developed for testing sheet material while the two other techniques are for bulk material. A comprehensive TEM analysis in the shear region of the hat-shaped specimens is carried out.

2. Experimental methods

Split Hopkinson bar setups are used for generation of the dynamic load on the material sample. These setups basically consist of two aligned bars with the specimen placed in between. A tensile, compression or torsion stress wave, generated at the free end of the input bar propagates along the input bar towards the specimen. This wave interacts with the specimen and is partly reflected back into the input bar and partly transmitted into the output bar. The strain histories corresponding with the loading, reflected and transmitted wave are measured by means of strain gauges attached on the Hopkinson bars. From those waves, the total force and deformation history of the specimen is determined, based on the principles of one-dimensional elastic-wave propagation in slender bars. Strain rates achieved with the Hopkinson technique are typically in the order of $10^3 s^{-1}$.

The three different shear test techniques with the corresponding specimen geometries are shown in Figure1: tensile, compressive and torsional split Hopkinson setup. For sheet materials the *planar shear sample* is used. The specimen geometry is optimized by finite element simulations to obtain an almost pure shear stress state in the plastic deforming region in the Ti6Al4V specimen, even at large strains. The specimen cannot only be used to study the constitutive material behaviour at low and high strain rates but also for studying fracture properties at low stress triaxiality. For bulk materials the axis-symmetric *hat-shaped specimen* is used to obtain very high shear strains in a narrow zone [3]. Because the stress state is a combination of shear and compression a much higher shear strain can be achieved before fracture, in comparison with the other test techniques. A stopper ring is used to interrupt the experiment in order to avoid destruction of the shear band so that it can be studied post-mortem. Although, the specimen is suited to generate shear bands at a known location, the complex stress distribution together with the subsurface shear zone hamper determination of stress and strain. The average stress can be estimated by the ratio of the test force and the shear surface while the strain is much more difficult to determine. Constitutive shear stress-strain data from the bulk material can more accurately be obtained by *torsion tests* on *thin-walled tubular specimens*. The torsion test has several advantages: a relatively homogeneous strain distribution, no edge effects in the circular shear zone and a pure shear stress state predominates. The specimen shown in Figure 1c has a gauge length of 2mm. To ensure strain localization in the centre of the gauge section, there is a small variation in the specimen wall thickness with a minimum 0.4mm.

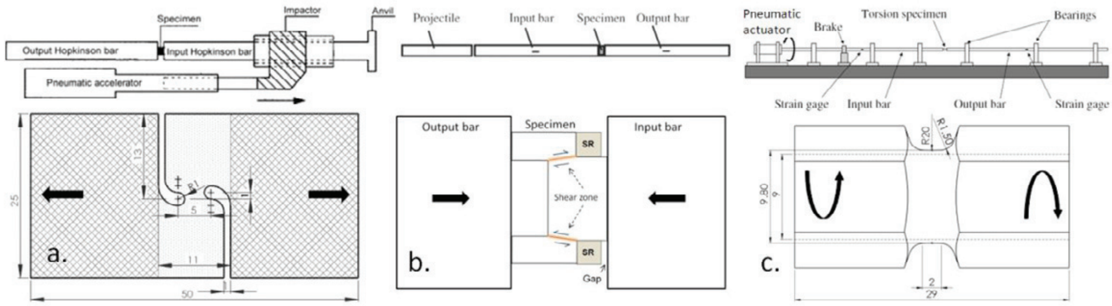

Fig. 1. Principle of three shear tests and respective specimen geometry: hat-shaped specimen test, planar shear test and torsion test.

For the TEM analysis, a Tecnai© microscope operated at 200kV was used to perform conventional electron diffraction, bright and dark field imaging. Analytical measurements to obtain spatially resolved compositional information were performed at the same microscope but operated in STEM mode (scanning transmission electron microsopy) using an energy dispersive X-ray (EDX) detector.

3. Experimental results

3.1. Planar shear test

In both the static and the dynamic tests the specimens fail without necking or clear evidence of micro-damage. Two clear differences are found between the specimens deformed statically and dynamically: 1. the region with visibly deformed grains is much smaller in the dynamically deformed specimen (±0.8mm) compared with the statically deformed specimen (±2mm) and 2. a narrow band of only a few micrometers, without visible grains is observed in the fracture plane of the dynamically deformed specimen (Fig. 3). Since it is impossible to interrupt the test before the specimen fails completely it is difficult to study the shear band in this type of experiment.

3.1. Hat-shaped compression test

In the hat-shaped specimens, shear bands are formed along the line connecting the inner and outer corner as is illustrated on Figure 1b. The shear band is not a static structure. Its shape and characteristics change quickly during deformation. Furthermore, unlike the specimen geometry the shear band is not axis-symmetric and has a varying shape around the specimen. Thus by studying the shear band in specimens with different indentation and at different locations in the same specimen, the evolution of the shear band can be observed. In the following, two specimens will be considered: Exp1 is interrupted before the drop of the force while Exp2 is deformed beyond as can be seen on Figure 2a. Figures 2b, c and d show optical images of the shear region. Figures 2b and 2c are both from Exp1 but at a different location along the circumference of the specimen. In Figure 2b a band of ±30μm with elongated grains can be seen while in Fig 2c this wide band has disappeared and a very narrow band of ±2μm without visible grains is observed. In the shear zone of the specimen from Exp2 a similar band with a width of ±6μm is found (Figure 2d). The microstructure inside these bands will be studied in §4.2.

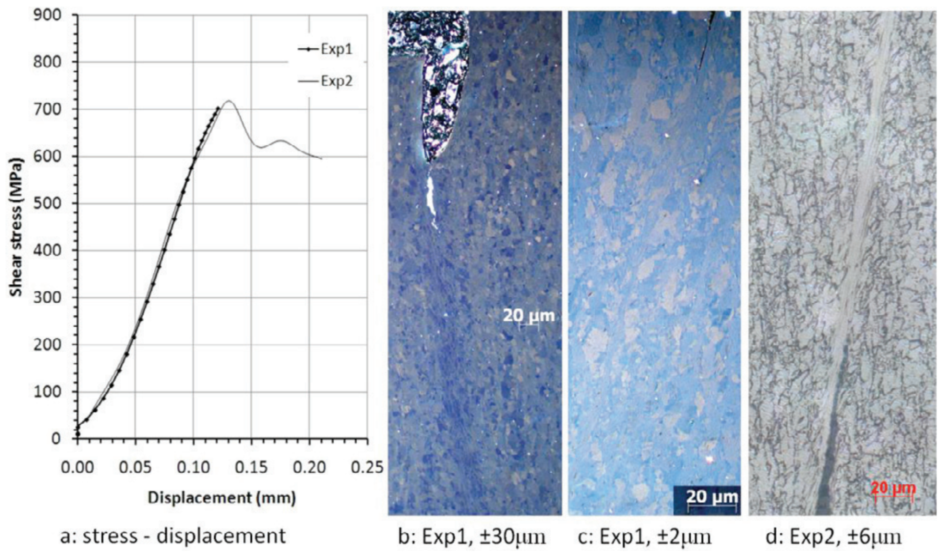

Fig. 2. a. Average shear stress-displacement curve of two hat-shaped specimen experiments. The average specimen deformation speed is around 2m/s in these tests b. and c. optical microscopy image from Exp1 and d. from Exp2.

3.2. Torsion test

A number of high strain rate torsion tests have been carried out on the same material as the hat-shaped specimens. Optical microscopy and SEM images from the shear zone are similar to the images from the planar shear specimen (Figure 3). Few elongated voids can be found near the fracture.

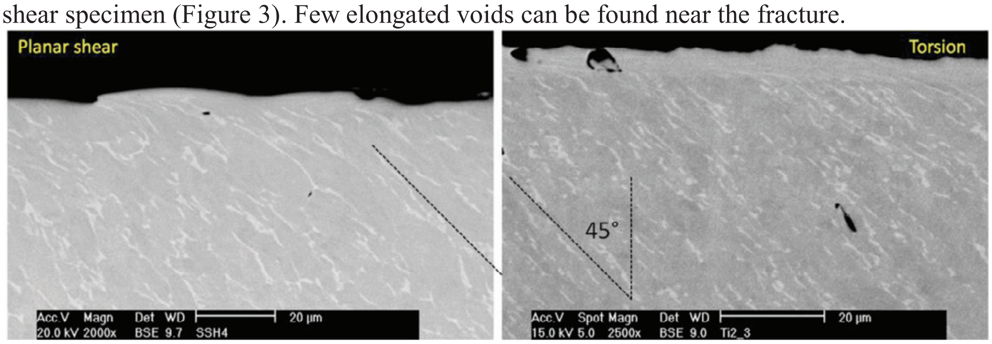

Fig. 3. SEM image in the shear region next to the fracture from planar and torsional shear specimen. A indicated 45° angle corresponds with a (simple) shear strain of γ=0.5. The average fracture γ measured from 4 torsion experiments is ±0.46.

4. TEM study

4.1. Specimen preparation

A TEM analysis is done to obtain more microstructural information from the shear bands firstly observed with optical microscopy (Fig. 2). First a slice parallel to the cylinder axis is made, as close as possible to the symmetry axis of the sample. From this slice a 3 mm disk is drilled which is subsequently ground to a thickness of 120μm. Dimpling is performed on the place where the shear band is expected to occur. Finally a perforated sample is made by electro-polishing using a twin-jet system, followed by an extra ion-milling step to enlarge the electron transparent area and have the shear band within this area.

4.2. Grain size and orientation

A different grain morphology is observed in the test with low (Exp1) and high deformation (Exp2). In the specimen of *Exp1*, the shear band shows grains of very small size in a band of only 1-3μm (Fig. 4a). A diffraction pattern obtained from a 0.7μm diameter area (Fig. 4b) shows a ring like structure indicating a strong grain fractioning and rather large changes in orientation. The circular patterns are evaluated and compared with the lattice spacings of α and β phase (Fig. 4b). These patterns show that α is the major phase, but that in addition the beta phase is present. Since the β phase also shows up more like a ring this indicates it is strongly deformed as well. Ring like SAED diffraction patterns are also found in a region with a diameter of only 200nm.

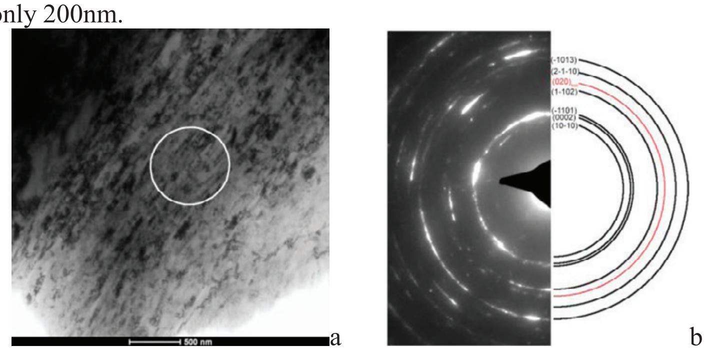

Fig. 4. Analysis of circular like diffraction patterns from within the nano-sized region from the specimen of Exp1

For the more severely deformed specimen from *Exp2*, no nano-sized grains are found such as in the specimen from the early interrupted Exp1. Figure 5a shows a BF image in the region with the expected shear band, indicating narrow and fractioned grains, but not as severe as in the case of Exp1. A band like morphology of elongated plates, resembling α' martensite is found a few tens of micrometers away from the expected shear band, as is illustrated in Figure 5b. However a more thorough analysis is necessary to confirm this. Figure 5c, obtained a bit further (±50μm) from the region of maximal shear shows the presence of {10-11} twins, which are not commonly encountered in titanium.

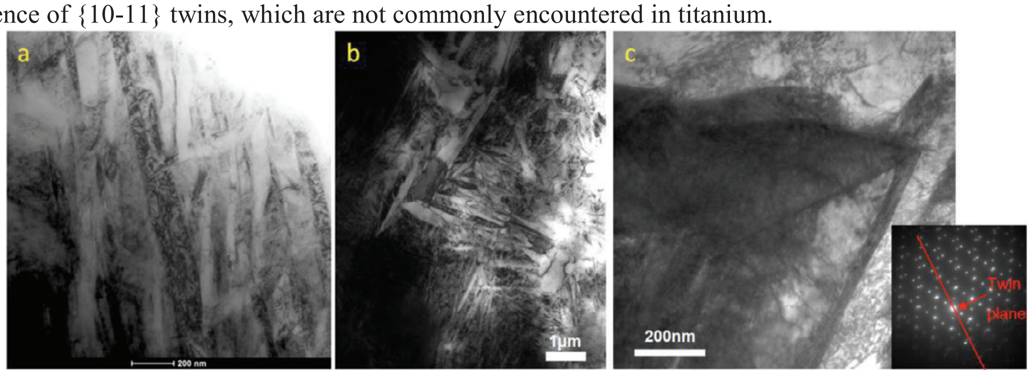

Fig. 5. Exp2: a. BF image in the region with highest shear deformation, b. BF image showing the plate shaped grain morphology next to the shear band and c. BF image and diffraction pattern of {10-11} twin found at a short distance from the shear band.

4.3. Composition

First EDX measurements are performed on the α and β phase of undeformed Ti6Al4V. In case of the α phase the composition is Ti: 89.4wt%, Al: 8.0wt%, V: 2.6wt% and no trace of Fe. For the β phase Ti: 79.9wt%, Al: 4.0wt%, V: 15.4wt% and Fe: 1.5wt%. Al is an α stabilizer and V a β stabilizer.

Secondly, using EDX analysis in STEM mode, compositional profiles and maps are made in the nano-crystalline area (Fig. 6a). The local elemental composition of the material along a path corresponds with the composition of either the undeformed α or β phase. In this way, distinction is made between α and β phase. The distribution plots of Fig. 6b show that the α and β regions are band-like. The compositional profile shown in Fig. 6c shows that the width of these bands is smaller than 100nm.

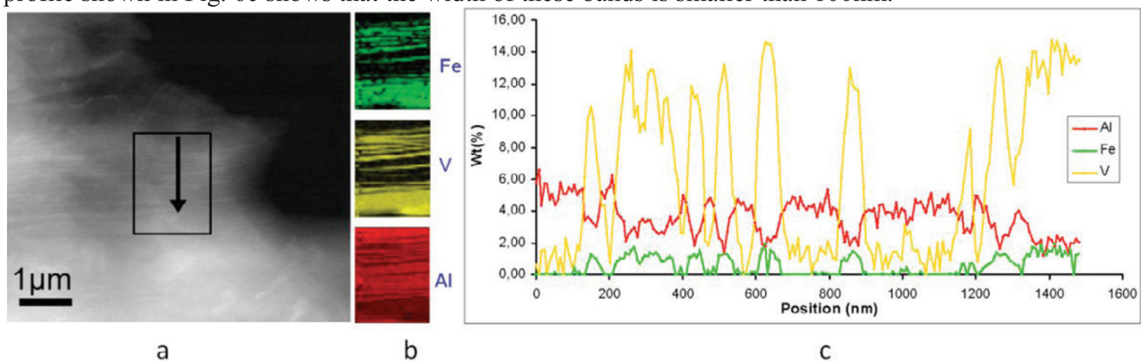

Fig 6. a. HAADF STEM image of the nano-crystalline region in the sample of Exp1, b. elemental distribution plot corresponding with the squared area in fig 6a and c. compositional profile corresponding along the black arrow

5. Conclusions

Three high strain rate shear techniques have been applied on Ti6Al4V. Complementary information about the fracture behaviour, including the formation of adiabatic shear bands is retrieved. The use of interrupted shear tests enables studying the shear band formation at different levels of strain. A TEM analysis shows that many different microstructures are formed inside and nearby the band: from very elongated grains to a fractioned nanocrystalline microstructure, martensite and twins. Inside the shear band, band like structures with an elementary composition corresponding with the α and β phase are observed. It is not excluded that each band still consists of multiple grains.

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